Spontaneous Strong CP violation in Heavy-Ion Collisions

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Theory Basics

QCD:

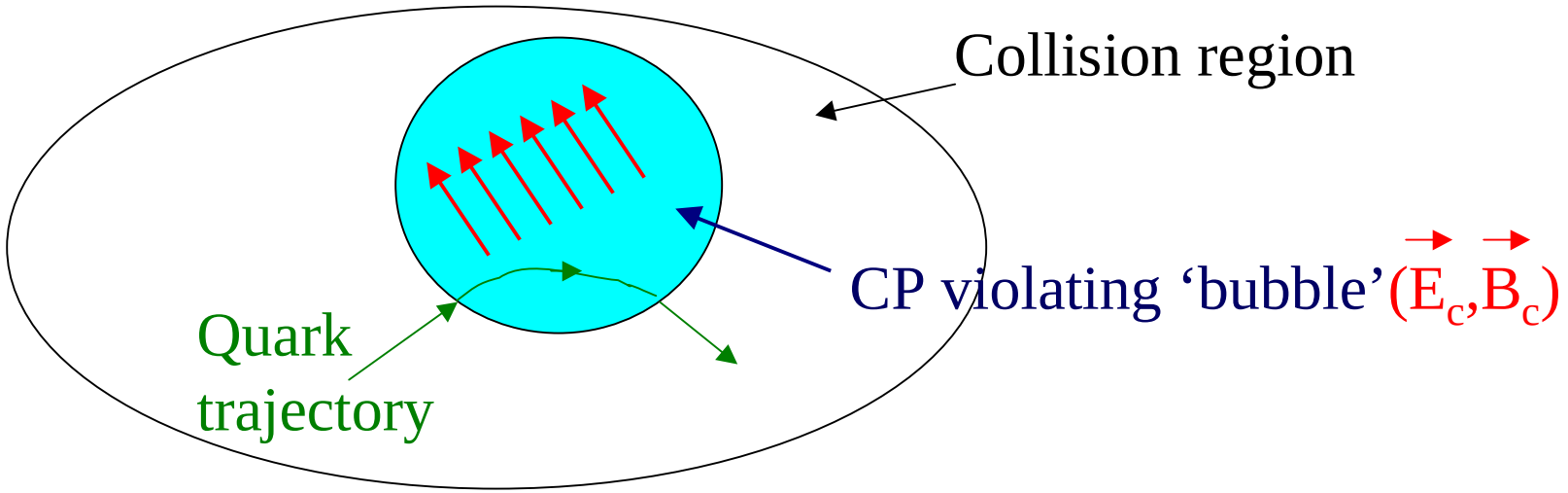
"should " include CP violation:

$$L_{QCD} \xrightarrow{axial\_anamoly, vacuum\_effects} L_{QCD} + \theta G_{\mu\nu}\tilde{G}^{\mu\nu} \left(\propto \theta \vec{E}_c \bullet \vec{B}_c\right)$$

but does not: experimentally, $\theta = 0$

Heavy-Ions: D. Kharzeev et al. from effective Lagrangian model propose that under certain conditions around a deconfining phase transition, regions of space may be formed which behave as if $\theta \neq 0$ -spontaneous CP violation.

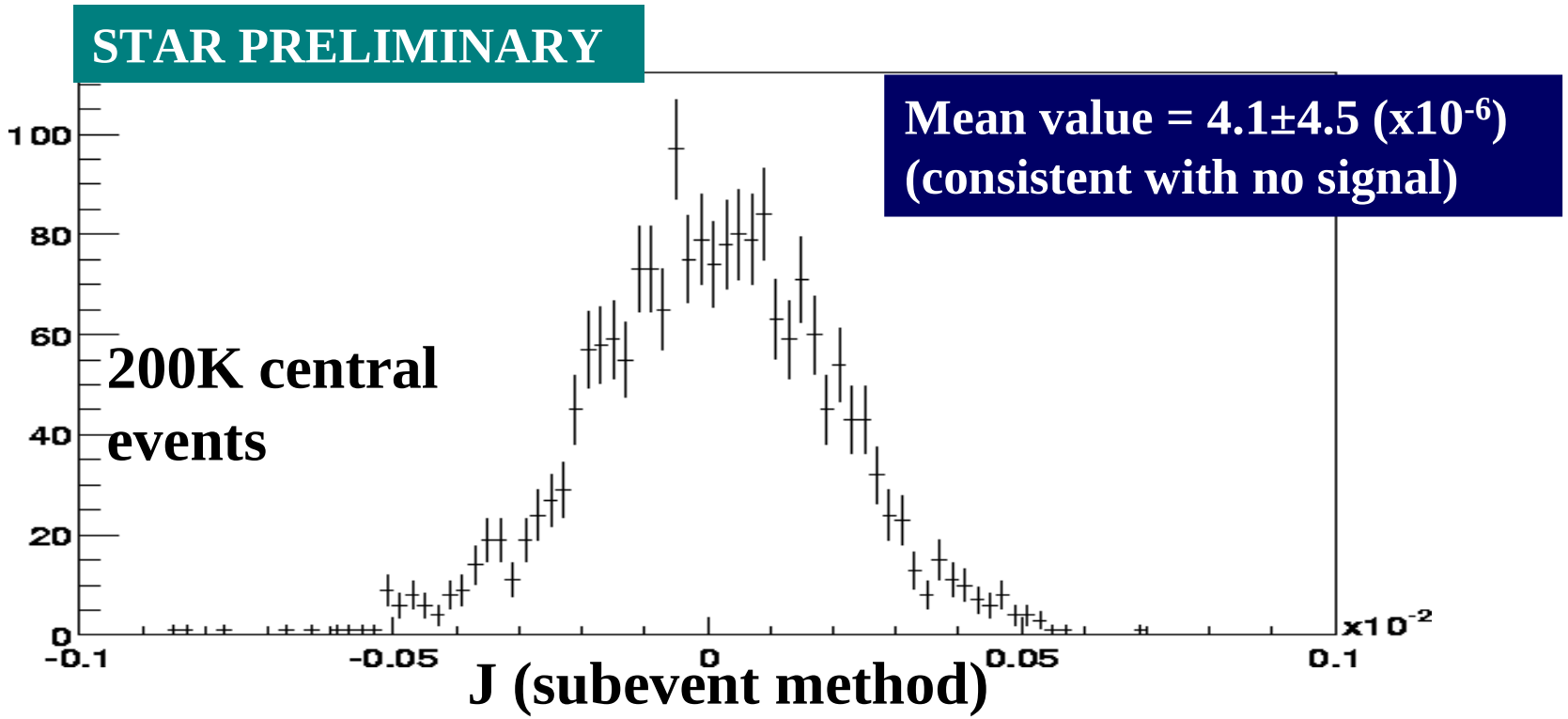
How to Observe this?: Original Idea...



Aligned E,B fields should alter particles' momentum space distributions in distinct ways $\Rightarrow$ look at global observables built out of particle momenta, e.g.

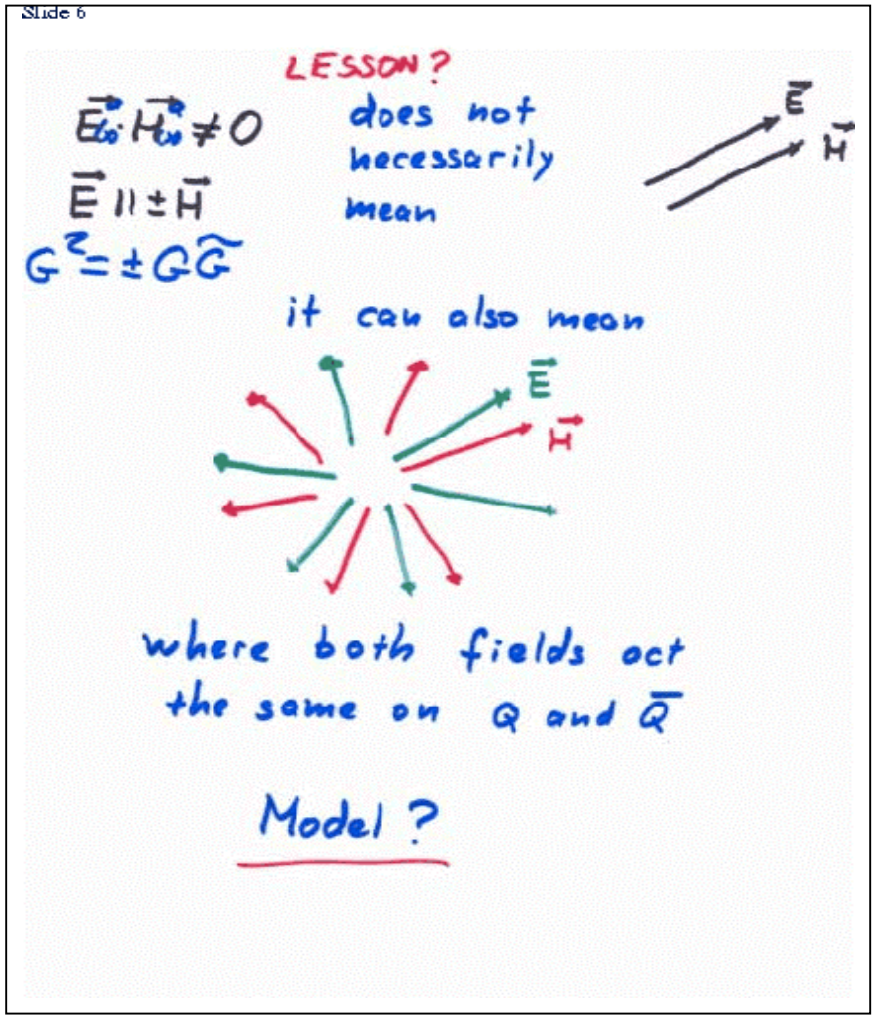
$$J = \frac{1}{N_{pairs}} \left\{ \sum_{+,-} (\hat{p}^+ \times \hat{p}^-) \,\mathrm{sgn}(\, p_z^+ p_z^-) \right\} \bullet \left(\sum_{+} \hat{p}^+ - \sum_{-} \hat{p}^- \right)$$

From Year-1 Data...



- No signal in 200K central events. But for nominal strength of the effect suggested by D. Kharzeev, would need ~30M events

Upon Further Consideration...



- With this new idea for field configuration, much more difficult to find momentum space asymmetries.

⇒Latest Idea

- P-odd bubbles are characterized by non-zero topological charge:

$$\nu[G] = \frac{g^2}{32\pi^2}\int d^4x\, \mathrm{Tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$

and cause chirality violation:

$$\Delta Q_5 = 2N_f\,\nu[G] = N_R - N_L$$

⇒ may be possible to observe helicity correlations in quarks through resultant helicity correlations in hyperons (lambdas). The observable effect would be non-statistical fluctuations in the number of + helicity lambdas on an event-by-event basis.

19.1 Fermion number nonconservation in parallel E and B fields.

(a) Show that the Adler-Bell-Jackiw anomaly equation leads to the following law for global fermion number conservation: If N_R and N_L are, respectively, the numbers of right- and left-handed massless fermions, then

$$\Delta N_R - \Delta N_L = -\frac{e^2}{2\pi^2} \int d^4x \, \mathbf{E} \cdot \mathbf{B}.$$

How Large an Effect?

Rough estimate (D. Kharzeev) assumes:

- Width of Q (topological charge) distribution ~ 10.

- Each unit of Q in a given event leads to one flip of one spin -1/2 particle's helicity.

- ~One third of produced quarks will be strange, ~1/10 of strange quarks go to (primordial) Λ production. Λ spin determined by s quark spin.

How Many Events to Observe With Future STAR?

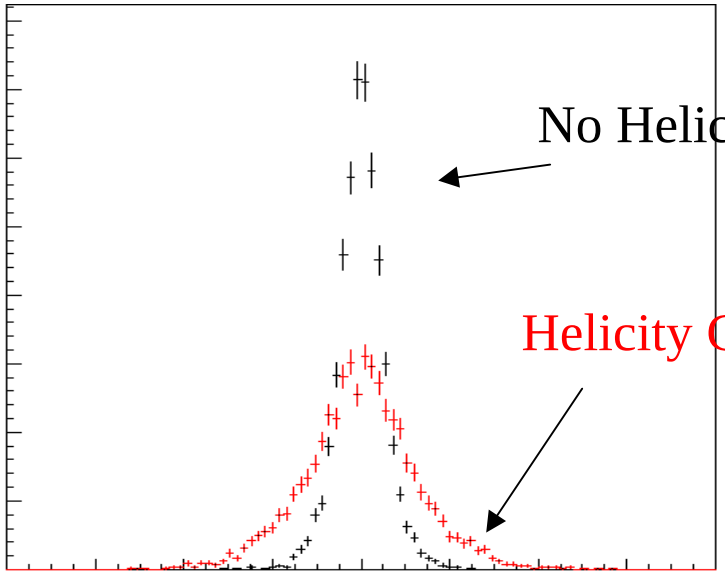
Assume:

- Acceptance over 2 units of rapidity,50% efficiency for Λ, $\overline{\Lambda}$.
- weak decay feed down to Λ can be mostly eliminated.
- Effect has 40% chance of happening within acceptance in a given event.

$\Rightarrow$From a rough calculation (not a detector simulation), we estimate that we would need ~ 45 million events to see a 3σ effect

Rough Outline of Analysis

Main Idea : Look at event-by-event distribution of $N_\uparrow /(N_\uparrow + N_\downarrow)$.

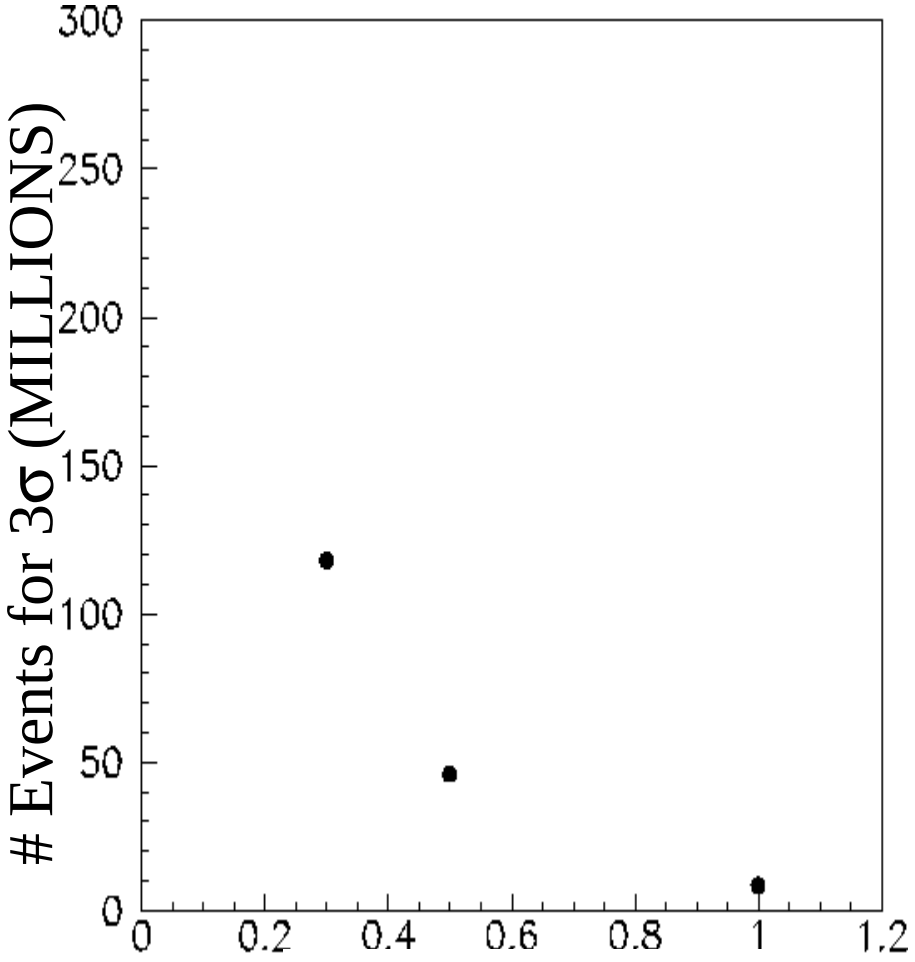


$N_\uparrow /(N_\uparrow + N_\downarrow)$

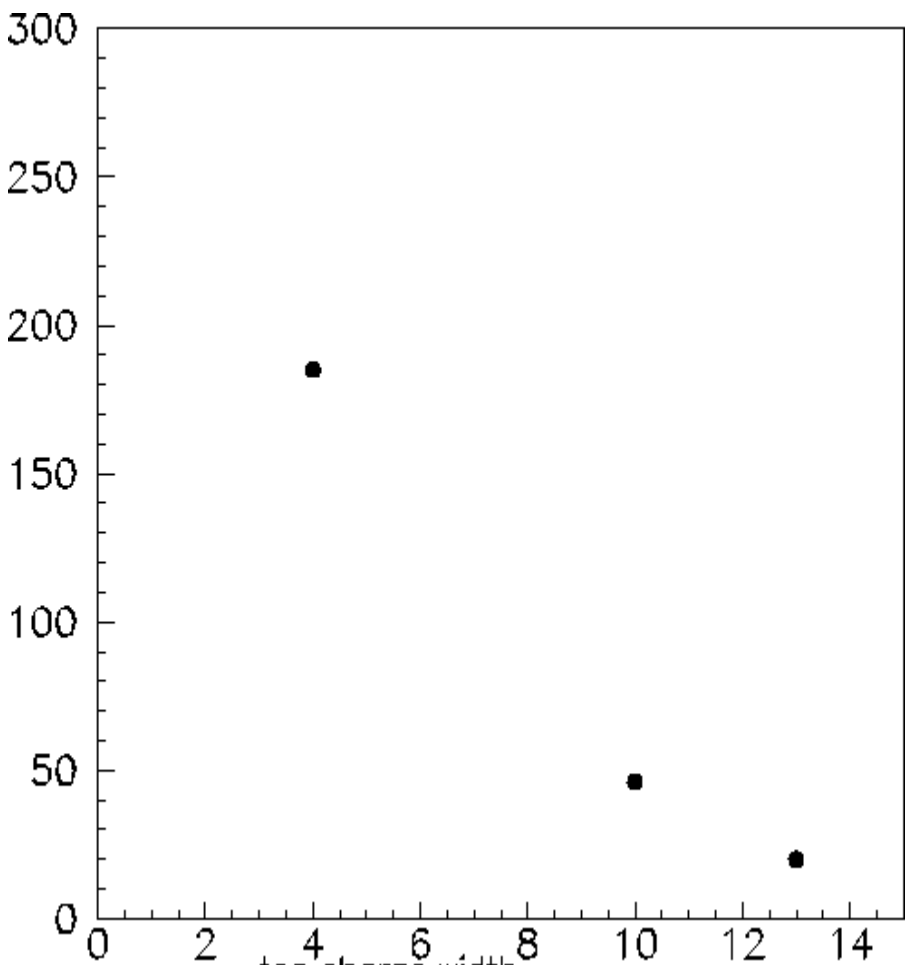
More Detail:

- For each event, we measure a certain number of Λ's, N_T, and a certain number of these, $N_\uparrow$, decay with proton along Λ line of flight.
- Compute the probability P_i for event 'i' of getting $N_\uparrow$ from N_T if all helicities are independent.
- Compute $\Pi_i P_i$ to get liklihood over whole event sample. Compare with value of $\Pi_i P_i$ from reference samples thrown from binomial distributions to normalize this probability.

Number of events needed vs...



Λ Efficiency



Q distribution width

Shouldn’t be problems...

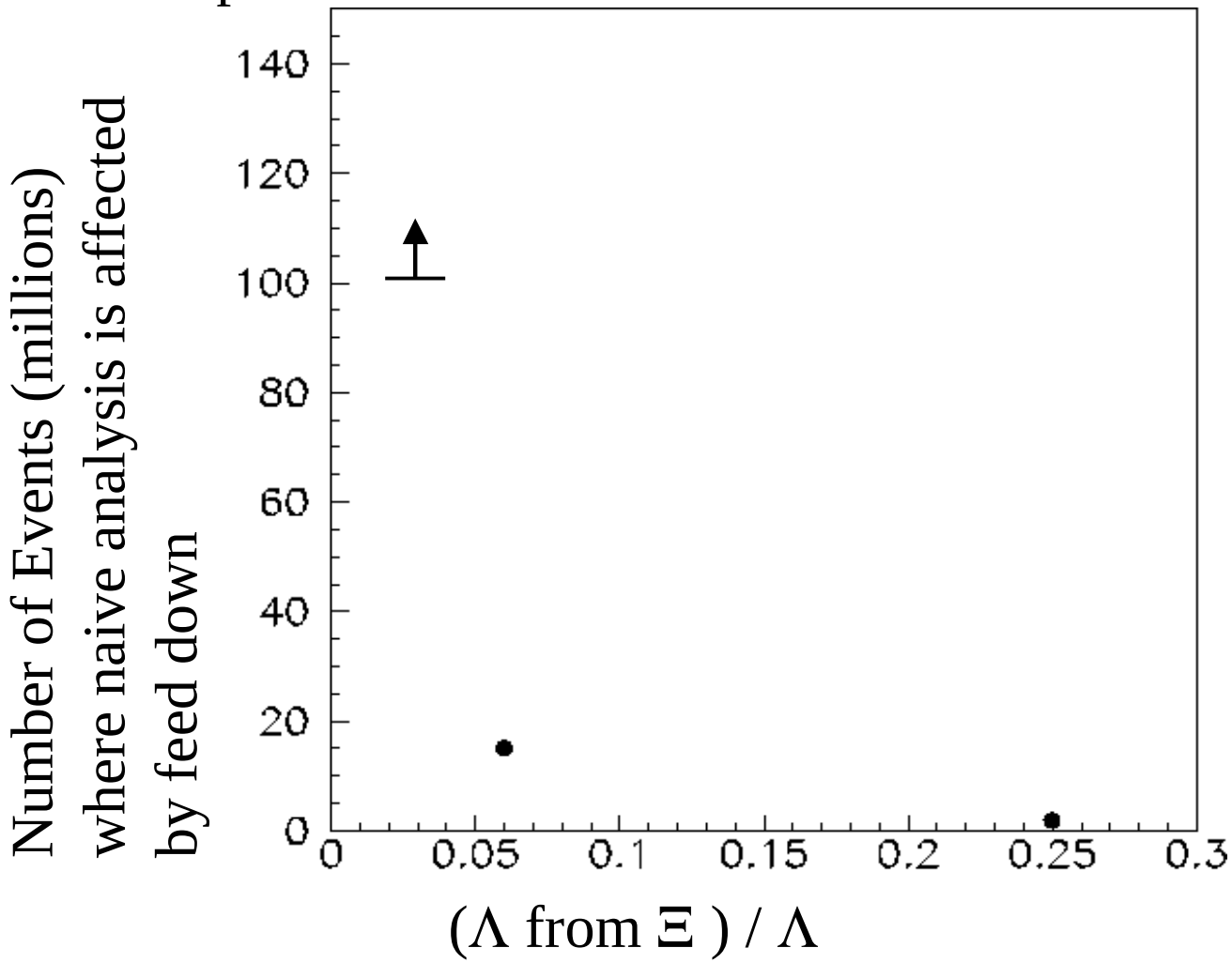
- Λ-Λ spin correlations (can be distinguished from helicity correlations by angular dependence in Λ-Λ c.o.m.
- Λ spin precession (for B=.5T, $\omega \approx 1.5 \times 10^{7}$ rad/s, $\tau_{\Lambda} \approx 3 \times 10^{-10}$ s)

Could be problems...

- Ξ feed down (not a false signal, but may complicate statistical analysis).
- Correlated efficiencies
- Different Efficiencies for +/- helicities varying as a function of y,p_T, azimuth, vertex position.

Ξ feed down

- Ξ feed down creates longitudinally polarized Λ s. This is not necessarily a problem, but may at least make statistical analysis more complicated.



Summary

- Strong CP violation would be significant physics discovery.
- Rough (and probably optimistic) estimate is that ~100M central events are needed (given a Λ efficiency of ~0.5)
- Very good Λ , Ξ efficiencies (i.e. very good vertex finding) are critical
- Work to do : need better theoretical estimates of signal size and more complete understanding of how varying efficiencies could affect this analysis.
- Also: work of R. Venugopalan indicates that forward rapidities may be more likely to contain regions of CP violating vacua.